PHYS 393
Low Temperature Physics
Set 6:

Superfluid He^3

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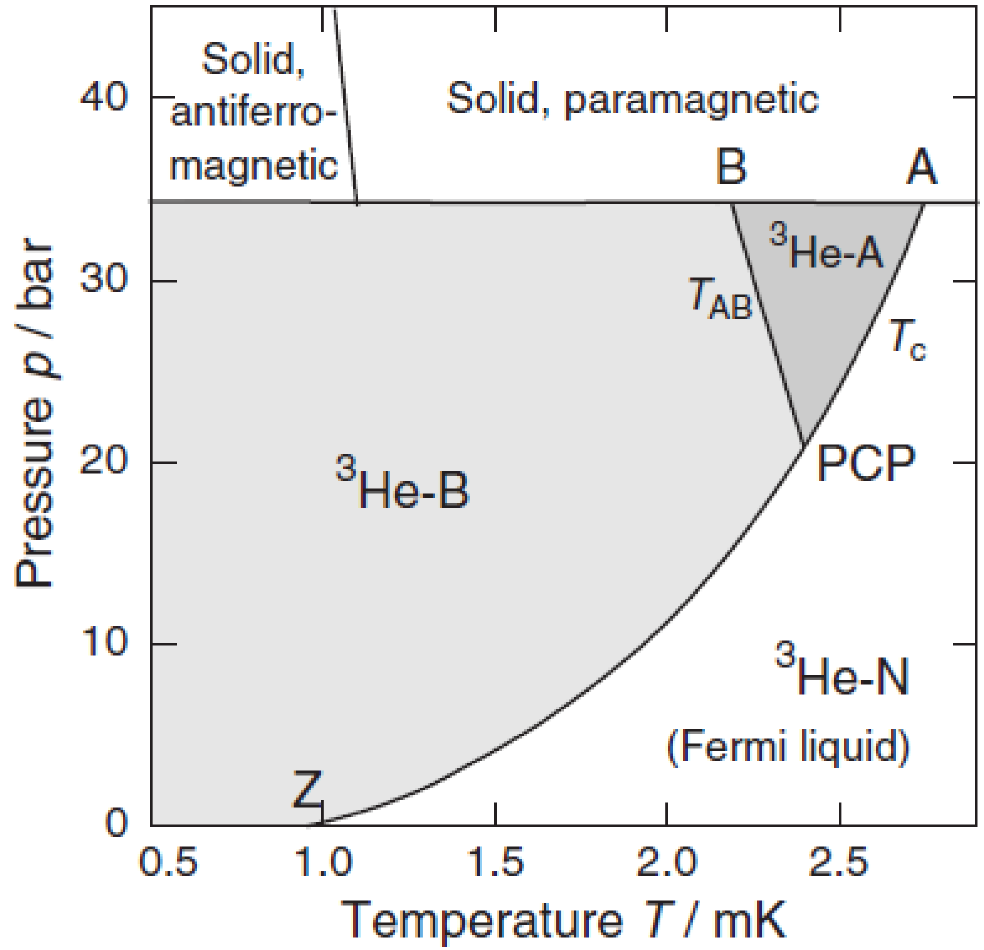
Superfluidity in He^3

- BEC condensation not possible in He^3 (fermions)
- BCS theory (1957) provided a mechanism
- Not exact analogy to superconductivity
- Many experimental efforts; problematic T_C theoretical estimates
- Discovery in 1971 around 2mK (Osheroff, Richardson, Lee)
- Initially thought it was a new solid phase
- Superfluidity soon proven by NMR experiments

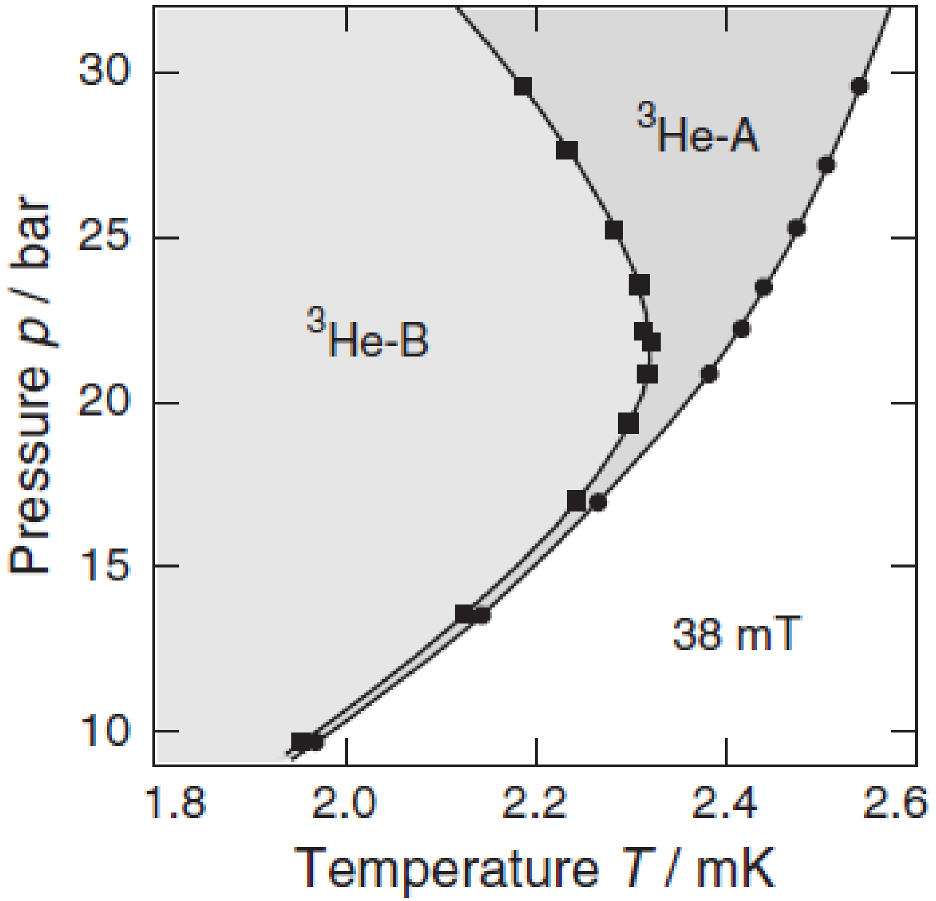
He^3 pressure-temperature phase diagram

- Behaviour below 3mK in absence of magnetic fields
- Two superfluid phases (shaded): A and B
- PCP: polycritical point (coexistence of three liquid phases)



He^3 phase diagram in magnetic field

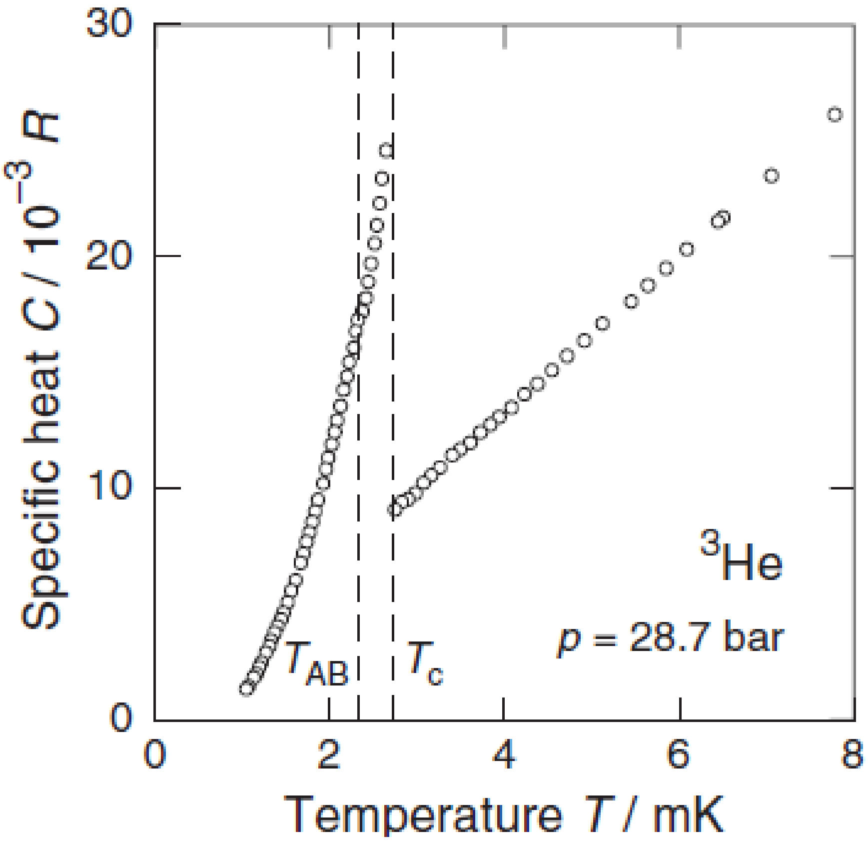
- Different behaviour in presence of magnetic field (graph for 38mT)
- PCP disappears
- Phase A widens
- Above 0.65T Phase B disappears



Phase transition

- Specific heat (graph): phase transition at T_C
- Small effect at T_{AB} (transition from phase A to phase B)

- Viscosity (damping of vibrating wire experiment): drop of damping force by 5 orders of magnitude between 1mK and 0.14mK
- Behaviour consistent with two-fluid model
- Proportion of superfluid increases as temperature decreases



Two-fluid model in He^3

- Superfluid seen as He^3 pairs in ground state
- Normal fluid seen as single He^3 atoms in excited states
- All superfluid as $T \rightarrow 0$
- Strength of pairing interaction determines critical temperature T_C
- Weak interaction: $T_C \sim 2mK$

Pairing mechanism

- Not phonons but magnetic interaction
  - First atom polarizes surrounding atoms
  - Second atom interacts with "polarization trail"
- Complex details
- In superconductors pairs have S=0, L=0
- He^3 atom pairs have S=1 (shown experimentally)
- Pauli principle requires total wavefunction to be antisymmetric WRT particle exchange
- Hence total orbital angular momentum must be odd – in practice L=1
- Superfluid He^3: pairs with S=1, L=1
  - Spin triplet or odd parity pairing

Spin-triplet pairing

Spin of pair determined by $\left|S, S_z\right\rangle$

Three different spin states:

$$S_z = +1 \quad \left|1,+1\right\rangle = \left|\uparrow\uparrow\right\rangle,$$

$$S_z = 0 \quad \left|1,0\right\rangle = \frac{1}{\sqrt{2}}\left[\left|\uparrow\downarrow\right\rangle + \left|\downarrow\uparrow\right\rangle\right],$$

$$S_z = -1 \quad \left|1,-1\right\rangle = \left|\downarrow\downarrow\right\rangle$$

Phase A contains S_z=+1, S_z=-1

Phase B contains S_z=+1, S_z=0, S_z=-1

Phase A is more magnetic than Phase B, as all pairs have non-zero magnetic moment

For field B>0.6T phase B disappears

New phase A1 appears as thin slice between normal fluid and Phase A, thought to be pure S_z=+1 or pure S_z=-1

Alignment

- He^3 superfluidity due to (weak) magnetic dipole-dipole interaction
- Pairs have perpendicular L, S vectors (minimizes energy)

Phase A:

- L vector perpendicular to container walls
- L vector perpendicular to S vector
- Inside magnetic field S vector aligns parallel to B vector
- Competing requirements produce complex, anisotropic effects

Phase B more complex

Conclusions on superfluid He3

- Atom-pair bosons
- Weak magnetic dipole-dipole interactions
- BEC condensate (pairs in ground state)

- Complex effects
- Strong effects from external magnetic and electric fields, container walls